

Natural Supersymmetry at the LHC

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Abstract

If the minimal supersymmetric standard model is the solution to the hierarchy problem, the scalar top quark (stop) and the Higgsino should weigh around the electroweak scale such as 200 GeV. A low messenger scale, which results in a light gravitino, is also suggested to suppress the quantum corrections to the Higgs mass parameters. Therefore the minimal model for natural supersymmetry is a system with stop/Higgsino/gravitino whereas other superparticles are heavy. We study the LHC signatures of the minimal system and discuss the discovery potential and methods for the mass measurements.

1 Introduction

The LHC experiments have started taking data to aim for the discovery of new physics. As one of the leading candidates for the new physics, various models of low energy supersymmetry (SUSY) have been constructed and their signatures have been studied. Especially, discovery and mass measurements in “representative” models such as the minimal supergravity and the minimal gauge mediation model have been extensively studied [1, 2, 3].

On the theoretical side, SUSY is motivated as a solution to the hierarchy problem. The electroweak symmetry breaking via the Higgs mechanism is naturalized by this space-time symmetry. However, when we closely look at the “representative” models used for the collider studies, we encounter a naturalness problem in the Higgs sector. The experimental lower bound on the Higgs mass requires a heavy scalar top quark (stop), which results in a delay of the cancellation of quadratic divergence.

The problem is, however, not model independent even within the context of the minimal supersymmetric standard model (MSSM). For example, the problem in the minimal supergravity model is the large logarithm, $\log M_{\text{Pl}}/m_{\tilde{t}}$ ($m_{\tilde{t}}$ and M_{Pl} are the stop mass and the Planck scale, respectively), in the radiative corrections of the Higgs mass parameter. The logarithm, $\log M_{\text{mess}}/m_{\tilde{t}}$ (M_{mess} is the messenger scale), can be small in the minimal gauge mediation model. However the small A -term is the problem in this case; the Higgs boson mass requires a very heavy stop otherwise the large A -term is required.

The conditions for the naturalness have been summarized in Ref. [4]: (a) light stops, (b) light Higgsinos, (c) a moderately large value of $\tan\beta$, (d) a large A -term and (e) a small logarithm.

In the discussion of the naturalness of the electroweak symmetry breaking, the most relevant parameter is the stop mass due to the large top Yukawa coupling and the color factor. In the MSSM, the stop mass, $m_{\tilde{t}}$ (the geometric mean of the two stop masses), should be at most about 600 GeV for the fine tuning to be better than at the level of 10 % [5, 6, 4]. Here, a small logarithm (the low messenger scale) of $M_{\text{mess}} \sim 10$ TeV is assumed. Even with such a light stop, the lower bound on the Higgs boson mass from the LEP-II experiments [7] can be satisfied within the MSSM when the A -parameter (the stop-stop-Higgs coupling) is as large as of order the stop mass [8, 9, 4, 10]. (See [11, 12] for the study of the A -parameter dependence of the Higgs boson mass in the MSSM.) Imposing the absence of significant fine tuning at the level of 10%, the naturalness upper bound on $m_{\tilde{t}}$ (which gets severer from above for a large A -parameter) and a large stop mixing through the large A -parameter

required from the Higgs boson mass constraint imply that the lighter stop should be lighter than about 400 GeV for $M_{\text{mess}} \gtrsim 10$ TeV.

Other sfermions and gauginos (gluinos, Winos and Binors) can be as heavy as a few TeV without affecting the naturalness of the electroweak symmetry breaking. On the other hand, as the supersymmetric Higgs mass μ is added up to the soft supersymmetry breaking Higgs mass parameters, μ (the Higgsino mass) should be of the electroweak scale to be natural.

The superparticle spectrum is important when we discuss signatures at the Large Hadron Collider (LHC). If we take the naturalness seriously in supersymmetric models, we see that there should be significant amount of the stop production at the LHC. If other sparticles except for the Higgsinos are heavier than 1 TeV, superparticle productions will be dominated by lighter stops and they all decay into Higgsinos directly. This is the minimal model of natural SUSY at the LHC, that is simply a system with a stop and Higgsinos (two neutralinos and a chargino). The requirement of the small logarithm implies a low energy SUSY breaking scenario (see [13, 14, 15, 16] for an interesting exception), and thus we also include the nearly massless gravitino, to which the lightest Higgsino can decay.

In the case where the Higgsino is heavier than the stop, the stop directly decays into a top quark and a gravitino if open. Those events look like $t\bar{t}$ productions. We will not consider such a case in this paper. See Ref. [17] for a study of such an event topology. In the case where the top quark is not open, the stop undergoes the three body decay into b , W and the gravitino. Such a case has been studied in Ref. [18].

There are attempts of model-building and studies of collider signatures with similar motivations. More minimal supersymmetry [19] has the first two generation particles at around 5 to 20 TeV to solve supersymmetry flavor and CP problems while keeping the naturalness for the electroweak symmetry breaking. In Ref. [20], a signature of a large A -term at the LHC has been discussed. See the partial list of recent related works in [21, 22, 23, 24, 25, 26].

In this paper, we study LHC signatures of a model with light stops, light Higgsinos and a (nearly) massless gravitino. As we have discussed, it is well-motivated to consider a very light stop such as $m_{\tilde{t}} \sim 200$ GeV. With such a light colored particle, the LHC will be very powerful. We assume that other superparticles are heavy enough to be ignored or even absent as particle states by directly coupling to the SUSY breaking sector (see *e.g* [27]). Such a spectrum is also motivated by the constraints from CP-violation and flavor physics. The SUSY events with the largest cross section are therefore a pair production of the lighter stop. The main decay mode of the stop is into a bottom (b) quark and a chargino. The chargino

subsequently decays into a neutralino and soft jets or leptons which we can ignore due to a small mass splitting between the charged and the neutral Higgsinos. The neutralino then decays into a Z boson or a Higgs boson and a gravitino.

The final state is $2b + 2Z$, $2b + hZ$, or $2b + 2h$ with missing momentum. We analyze these events and consider methods to find the stop. We also discuss the measurement of the stop and the Higgsino masses as well as the discovery of the Higgs boson through this process.

2 Naturalness upper bound on superparticle masses

We start with the review of the naturalness in electroweak symmetry breaking in the MSSM (see, e.g., [4] for a more detailed discussion). Generally in electroweak symmetry breaking via the Higgs mechanism, there is a relation between the Higgs boson mass (m_h) and the quadratic term in the potential (the negative mass squared), m^2 :

$$\frac{m_h^2}{2} = -m^2. \quad (1)$$

In the MSSM, m_h can be as large as 130 GeV [28, 29, 30]. For a moderately large value of $\tan \beta$, electroweak symmetry breaking is mainly due to the vacuum expectation value of the up-type Higgs field, H_u . In this case, the m^2 parameter has two sources:

$$m^2 = \mu^2 + m_{H_u}^2. \quad (2)$$

The first and the second terms are positive and negative, respectively. A fine tuning is required if there are contribution to $|m^2|$ which are much larger than $m_h^2/2 \lesssim (130 \text{ GeV})^2/2$.

An obvious conclusion from above is that the μ parameter (the Higgsino mass) cannot be very large. If we measure the fine tuning by $\Delta^{-1} = m_h^2/2\mu^2$ and require $\Delta^{-1} > 10\%$ for example, we obtain

$$|\mu| \lesssim 290 \text{ GeV}. \quad (3)$$

Another important contribution is from the stop-top loop diagrams to the $m_{H_u}^2$ parameter. There are two kinds of interactions in the diagrams; one with the top Yukawa interaction ($-y_t \bar{q}_3 u_3 H_u$) and another through the three-point stop-stop-Higgs interaction ($-A_t y_t \tilde{q}_3 \tilde{u}_3 H_u$). The three-point interaction also provides an important contribution to the Higgs boson mass, m_h . By assuming a small logarithm ($M_{\text{mess}} \sim 10 \text{ TeV}$), we obtain upper and lower bounds on the stop mass parameter ($m_{\tilde{t}} \equiv (m_{\tilde{q}_3} m_{\tilde{u}_3})^{1/2}$) from the naturalness and

the Higgs boson mass bound, respectively. Requiring $\Delta^{-1} > 10\%$ and $m_h > 114.4$ GeV [7], where $\Delta^{-1} \equiv m_h^2/2m_{H_u}^2|_{\text{rad}}$ with $m_{H_u}^2|_{\text{rad}}$ the stop-loop contribution, the bounds are

$$500 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 500 \text{ GeV}, \quad (4)$$

for $|A_t| \sim m_{\tilde{t}}$ and

$$250 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 360 \text{ GeV}, \quad (5)$$

for $|A_t| \sim 2m_{\tilde{t}}$. There is no allowed region for $|A_t| \lesssim m_{\tilde{t}}$ or $|A_t| \gtrsim 2.5m_{\tilde{t}}$. For $A_t = 0$, we obtain $\Delta^{-1} \lesssim 2\%^*$. The maximum value of Δ^{-1} is about 20% which can be achieved when $|A_t| \sim 2m_{\tilde{t}}$. The naturalness upper bound on the lighter stop mass is then,

$$m_{\tilde{t}_1} \lesssim 400 \text{ GeV} \quad (|A_t| \sim m_{\tilde{t}}), \quad (6)$$

$$m_{\tilde{t}_1} \lesssim 200 \text{ GeV} \quad (|A_t| \sim 2m_{\tilde{t}}), \quad (7)$$

for $\Delta^{-1} > 10\%$.

On the other hand, there is no tight naturalness constraint on other superparticles. The gaugino loop can contribute to $m_{H_u}^2$ or $m_{\tilde{t}}$, but the masses can be as large as a few TeV. Other sfermions can contribute $m_{H_u}^2$ or $m_{\tilde{t}}$ through the gauge interactions at two-loop level or through the Yukawa interactions at one-loop level. Again, masses at a few TeV do not cause a naturalness problem.

Therefore, the minimal set-up for natural supersymmetry is light stops and light Higgsinos; we ignore all other superparticles since the superparticle productions will be anyway dominated by the pair productions of the lighter stop. The requirement of the small logarithm implies low energy SUSY breaking scenarios such as gauge mediation [32, 33]. In that case, there is a nearly massless gravitino to which the lightest MSSM particle can decay promptly in collider experiments such as the LHC.

This minimal set-up is not particularly motivated by a known UV model of supersymmetry breaking. It is usually the case that the discussion of collider signatures of SUSY models requires an assumption of the whole spectrum and that is why a benchmark model has been needed. However, the fact that the naturalness consideration predicts a very light colored particle allows us to postpone the discussion of the detailed structure of the model or the spectrum. Conversely, one can test the naturalness principle by looking for a light stop and a light Higgsino.

*The bounds and values are sensitive to the top quark mass. We have used $m_t = 173$ GeV [31].

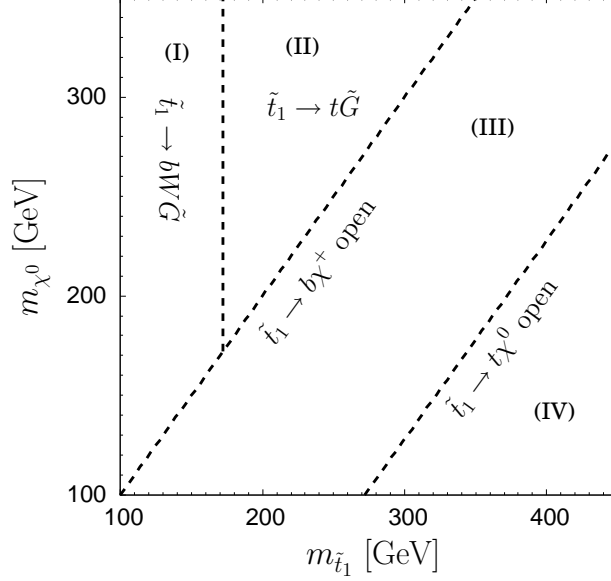


Figure 1: Parameter regions.

3 Natural SUSY at the LHC

In the study of the stop/Higgsino/gravitino system, there are four parameter regions which give distinct signatures at the LHC. In Fig. 1 we show the four regions (I)–(IV). If the Higgsino is heavier than the stop and the stop is heavier than the top quark (region (II)), the stop will decay directly into a top quark and a gravitino. The final state in this case is $t\bar{t}$ with missing momentum. Such events may not be easy to be distinguished from the $t\bar{t}$ events. See Refs. [34, 17] for a study of this event topology. The case with $m_{\tilde{t}} < m_t$ (region (I)) has been studied in Ref. [18]. There the differences in the distributions of kinematical variables between the signal and the $t\bar{t}$ events have been discussed.

In this study, we assume the lighter stop is heavier than the Higgsino, and the Higgsino decays into the gravitino (regions (III) and (IV)). The final states are very different from the case with regions (I) and (II). The main production process is the pair production of the lighter stops, and then the stops decay into the Higgsinos. The lightest Higgsino (which we assume to be neutral) in turn decays into Z or h (the lightest Higgs boson) plus a gravitino.

If the SUSY breaking scale (\sqrt{F}) is higher than about 100 TeV, the Higgsino lifetime is long enough to show a displaced vertex at the level of a sub millimeter. Such a situation has been studied in Ref. [35], and found that the LHC can discover the neutralino if $c\tau$ is around 10^{-1} – 10^5 mm by looking for displaced Z bosons ($\sqrt{s} = 7$ TeV with an integrated

luminosity of 1 fb^{-1}). If the displaced Z bosons are observed, they are a strong indication of the neutralino/gravitino system.

For \sqrt{F} smaller than about 100 TeV, which may be reasonable to assume from the requirement of a low messenger scale, the displaced vertex of the Higgsino decay will be difficult to observe. In such a case, the event topology resembles to the case with a stop/Higgsino/Bino system. We will discuss possible ways to distinguish those two scenarios later. In the following analyses, in particular in the mass measurements, we implicitly make an assumption that the Higgsino decays into a nearly massless gravitino, not a massive Bino. The assumption should be tested by other processes or by looking for displaced vertices.

3.1 Parameters

In the following we perform a Monte Carlo simulation of the SUSY events at the LHC. We use the following parameters for the Higgsino/stop sector:

$$m_{\tilde{q}_3} = m_{\tilde{u}_3} = 400 \text{ GeV}, \quad A_t = -800 \text{ GeV}, \quad (8)$$

$$\mu = 200 \text{ GeV}, \quad \tan \beta = 10, \quad (9)$$

and we take other superparticle masses to be 1 TeV so that one can ignore the production of those particles. The mass parameters $m_{\tilde{q}_3}$ and $m_{\tilde{u}_3}$ are the soft SUSY breaking masses for the left- and right-handed third-generation squarks, respectively. The relevant mass spectrum and branching fractions calculated from this parameter set are summarized in Table 1. The ISAJET package [36] is used for the calculation of the spectrum and the branching ratios. This sample point is in the region (III) in Fig. 1 where $\tilde{t}_1 \rightarrow t\chi_1^0$ is closed. The decay mode opens in region (IV), but since the $\tilde{t}_1 \rightarrow b\chi^+$ decay has a larger branching ratio in general, the following discussion can also apply in region (IV).

The stop masses are 230 GeV and 560 GeV, with which the cross sections of the squark-pair productions are

$$\sigma_{\tilde{t}_1\tilde{t}_1} = 18 \text{ pb}, \quad \sigma_{\tilde{t}_1\tilde{t}_2} = 0.10 \text{ pb}, \quad \sigma_{\tilde{t}_2\tilde{t}_2} = 0.11 \text{ pb}, \quad \sigma_{\tilde{b}_1\tilde{b}_1} = 1.1 \text{ pb}, \quad (10)$$

for pp collisions at $\sqrt{s} = 14 \text{ TeV}$. As one can see, the SUSY events are dominated by the pair production of the lighter stop. The typical event is depicted in Fig. 2. In our analysis, we have produced the hadronized signal events by the HERWIG event generator [37, 38]. For background processes, we have used ALPGEN [39] and HERWIG. The detector simulation is based on the AcerDET package [40]. We assume 60% b -tagging efficiency and the mistagging rate to be 10% (1%) for the charm quark (other light quarks).

particle	mass [GeV]	branching ratio
χ_1^0	193.8	$\text{Br}(\chi_1^0 \rightarrow \tilde{G}Z) = 0.80,$ $\text{Br}(\chi_1^0 \rightarrow \tilde{G}h) = 0.20$
χ_2^0	202.8	$\text{Br}(\chi_2^0 \rightarrow \chi_1^0 q \bar{q}) = 0.40,$ $\text{Br}(\chi_2^0 \rightarrow \chi_1^0 \nu \bar{\nu}) = 0.19,$ $\text{Br}(\chi_2^0 \rightarrow \chi_1^\pm q \bar{q}) = 0.13, \dots$
χ_1^+	197.3	$\text{Br}(\chi_1^+ \rightarrow \chi_1^0 q \bar{q}) = 0.67,$ $\text{Br}(\chi_1^+ \rightarrow \chi_1^0 l^+ \nu) = 0.33$
\tilde{t}_1	230.6	$\text{Br}(\tilde{t}_1 \rightarrow \chi_1^+ b) = 1.0$
\tilde{t}_2	559.4	$\text{Br}(\tilde{t}_2 \rightarrow Z \tilde{t}_1) = 0.38,$ $\text{Br}(\tilde{t}_2 \rightarrow W^+ \tilde{b}_1) = 0.20,$ $\text{Br}(\tilde{t}_2 \rightarrow \chi_1^0 t) = 0.16,$ $\text{Br}(\tilde{t}_2 \rightarrow \chi_1^+ b) = 0.16, \dots$
\tilde{b}_1	404.1	$\text{Br}(\tilde{b}_1 \rightarrow W^- \tilde{t}_1) = 0.73,$ $\text{Br}(\tilde{b}_1 \rightarrow \chi_1^- t) = 0.24, \dots$
h	119.6	$\text{Br}(h \rightarrow b \bar{b}) = 0.82, \dots$
\tilde{G}	~ 0	

Table 1: The mass spectrum and the branching ratios used in the analysis.

3.2 Discovery of the light stop

We study discovery potential of the light stop at the early stage of the LHC experiments. Once the stop pair is produced, they decay into $b\chi_1^+$ with almost the 100% branching ratio. The charginos χ_1^+ subsequently undergo the three body decays into χ_1^0 and a quark or a lepton pair. Finally, χ_1^0 decays mainly into $\tilde{G}Z$. Here χ_1^0 and χ_1^+ degenerate in masses because they are both Higgsinos. Therefore, the quarks/leptons from the χ_1^+ decays are rather soft. A typical final state of the stop is then $2b + 2Z + \cancel{p}_T$ (Fig. 2).

We take the search strategy for the stop to be to look for $b + Z(\rightarrow l^+ l^-) + \cancel{p}_T$. The main backgrounds are $Z + \text{jets}$ and $t\bar{t}$ events. In order to reduce them, we impose the following selection cuts:

- at least one b -tagged jet with $p_T > 30$ GeV,
- $M_{\text{eff}} > 350$ GeV and $\cancel{p}_T > 150$ GeV,
- $85 \text{ GeV} < m_{l^+ l^-} < 95 \text{ GeV}$.

Here, \cancel{p}_T is a missing transverse momentum and M_{eff} is the effective mass [41] which is a scalar sum of visible and missing transverse momenta.

With an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$, the numbers of signal and background events passed through the cuts are 104 and 13, respectively. At $\sqrt{s} = 7 \text{ TeV}$, the cross sections for the $\tilde{t}_1 \tilde{t}_1^*$, $t\bar{t}$, and $Z + \text{jet}$ productions are approximately reduced by factors of

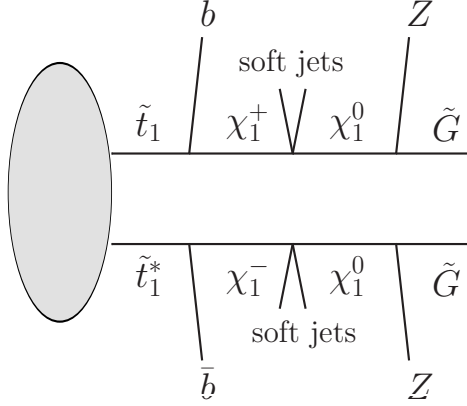


Figure 2: The typical decay chain of the lighter stop.

1/10, 1/6, and 1/3, respectively, compared to those with $\sqrt{s} = 14$ TeV, *i.e.*, approximately 10 events for 2 expected background event. Therefore, by looking for this channel, the lighter stop can be discovered at an early stage of the LHC experiments.

The same final states provide signatures with four leptons. Looking for this channel will be a non-trivial test of the scenario. The sensitivities at the LHC is similar to $bZ + \cancel{p}_T$. At the Tevatron, the cross section of the stop pair production is of the order of 100 fb^{-1} for $m_{\tilde{t}_1} = 230$ GeV. Considering the leptonic branching ratio of the Z boson, the four-lepton signature will be quite challenging to be observed at the Tevatron experiments.

3.3 Higgsino mass measurement

Now we turn to the analysis of mass measurements after the discovery. Although there are two missing gravitinos in each process, the theoretical input that the gravitino being massless and also the technique of M_{T2} [42] help to measure the Higgsino and stop masses. See Appendix A for the definition of M_{T2} .

We first discuss determination of the Higgsino mass. The lightest Higgsino χ_1^0 is mainly produced from the cascade decay of the stops which are produced in pair. Therefore, in each event, there are a pair of χ_1^0 . Because of the Higgsino nature, χ_1^0 subsequently decays into $Z\tilde{G}$ or $h\tilde{G}$.

The M_{T2} variable is suited for this situation as was studied in the Bino case in Ref. [43]. We apply the M_{T2} variable for the subsystem $\chi_1^0\chi_1^0 \rightarrow (Z\tilde{G})(Z\tilde{G}) \rightarrow (l^+l^-\tilde{G})(l'^+l'^-\tilde{G})$ in the cascade decays. The maximal value of the M_{T2} distribution gives the Higgsino mass if the

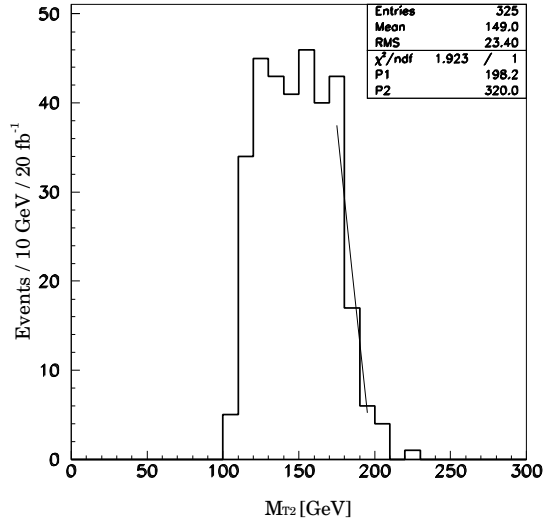


Figure 3: The Higgsino mass measurement. The M_{T2} distribution is shown for the $2Z + \cancel{p}_T$ system with an integrated luminosity of $\mathcal{L} = 20 \text{ fb}^{-1}$. The endpoint corresponds to the Higgsino mass.

true \tilde{G} mass is used in the calculation of M_{T2} . We use the leptonic decay channel of the Z boson in order to reduce the background from $t\bar{t}$ productions.

We reconstruct two Z bosons out of four candidate leptons in the final state. We require the Z candidates to be lepton pairs with the same flavor and the opposite charges. If all the four leptons have the same flavor, we take the combination in which the difference of the two reconstructed Z boson masses is smaller than the other combination. We impose the following cuts:

- four leptons ($p_T > 10 \text{ GeV}$),
- $85 \text{ GeV} < m_{l+l-} < 95 \text{ GeV}$,
- $M_{\text{eff}} > 250 \text{ GeV}$ and $\cancel{p}_T > 50 \text{ GeV}$.

In Fig. 3, we show the M_{T2} distribution for the $2Z + \cancel{p}_T$ system. We used a data set of 20 fb^{-1} . We assume \tilde{G} is massless and thus the maximal value of the M_{T2} distribution gives the χ_1^0 mass. We can see a clear endpoint around the input χ_1^0 mass, 193.8 GeV. As a demonstration, we fit the endpoint region with a linear function. We obtained the neutralino mass to be $m_{\chi_1^0} = 198 \pm 2 \text{ GeV}$. The numbers quoted here are sensitive to the choice of the fitting function and the region to fit. The corresponding error is not included here.

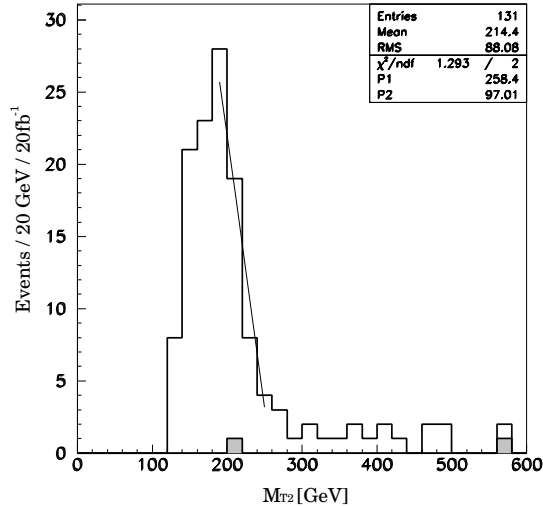


Figure 4: The stop mass measurement. The M_{T2} distribution is shown for $2Z + 2j + \cancel{p}_T$ system with an integrated luminosity of $\mathcal{L} = 20 \text{ fb}^{-1}$. The endpoint corresponds to the stop mass.

3.4 Stop mass measurement

One can also measure the stop mass by using the M_{T2} distribution by including two hard jets (see Fig. 2). We use a pair of (bZ) combinations as visible particles in the definition of the M_{T2} variable. Therefore we require at least two and less than five hard jets ($p_T > 20 \text{ GeV}$) in addition to the two Z boson candidates (four leptons). The Z boson candidates are selected in the same way as in the study of the Higgsino mass measurement. While attaching a hard jet, we need to decide which Z boson to combine. We take a strategy to select a combination which satisfies $m_{j_1 Z_1} + m_{j_2 Z_2} = \min_{i \neq j} (m_{j_i Z_1} + m_{j_j Z_2})$, where j_i is a label for hard jets.

We only use events in which at least either of j_1 or j_2 is b -tagged. This selection cut significantly reduces the background from $2Z + \text{jets}$ events. We therefore do not impose the M_{eff} and the \cancel{p}_T cuts in this analysis.

In Fig. 4, we show the M_{T2} distribution for the $2Z + 2j + \cancel{p}_T$ system for an integrated luminosity of 20 fb^{-1} . The hatched histogram is the background from the $2Z + 2j$ events. Again, by assuming that \tilde{G} is massless, the maximal value gives the stop mass. We can see a fall off of the histogram around the input stop mass, 230.6 GeV . By fitting the endpoint region with a linear function, we obtain the endpoint to be $m_{\tilde{t}_1} = 258 \pm 6 \text{ GeV}$. The error from the choice of the fitting function and the region to fit is not included here.

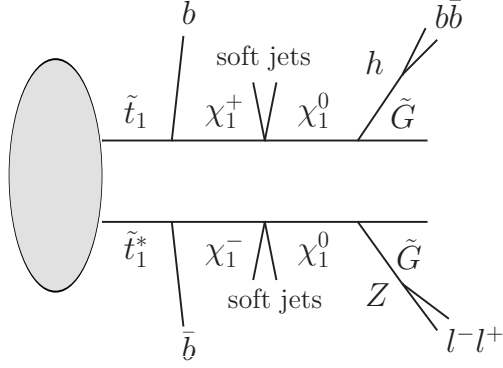


Figure 5: The decay chain for the Higgs boson search.

3.5 Higgs boson signal

An interesting signature of the light Higgsino is the production of the Higgs boson from its decay [44, 4, 45]. Here we try to look for an $m_{b\bar{b}}$ peak from the $h \rightarrow b\bar{b}$ decay (see Fig. 5). As candidate events we require the following:

- a lepton pair with the same flavor and opposite charge with $p_T > 10$ GeV,
- $85 \text{ GeV} < m_{l^+l^-} < 95 \text{ GeV}$,
- at least two hard jets with $p_T > 50$ GeV,
- at least three and less than five hard jets with $p_T > 30$ GeV,
- $M_{\text{eff}} > 250$ GeV,
- at least one of the two hardest jets is b -tagged.

There are two difficulties in looking for the Higgs peak. One is the large $t\bar{t}$ background which gives a similar final state. The other is the combinatorial background. There are always additional two b -jets from the stop decays.

The final state of the $t\bar{t}$ production with leptonic decays of W bosons contains two b -jets, two leptons and missing momentum, whereas the signal event is four b -jets, two leptons from a Z boson, and missing momentum by gravitinos. Although the final state is similar, there is an effective method to reduce the $t\bar{t}$ background by using the M_{T2} variable again.

We treat the two leading p_T jets (j_1 and j_2) as the Higgs boson candidates, and the lepton pair (l_1 and l_2) as the Z boson candidate. In order to reduce the $t\bar{t}$ background, we define

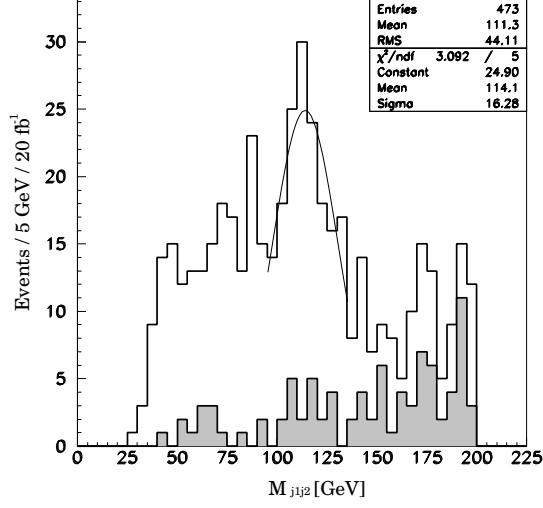


Figure 6: Invariant mass of the j_1 and j_2 with an integrated luminosity of $\mathcal{L} = 20 \text{ fb}^{-1}$.

the following M_{T2} valuable in this $2l + 2j + \cancel{p}_T$ system. We use $p_{j_1} + p_{l_1}$ and $q_{j_2} + q_{l_2}$ as the two visible momenta (which we define the $M_{T2}((j_1 l_1)(j_2 l_2))$), where the combination is selected so that it minimizes $m_{j_1 l_1} + m_{j_2 l_2}$. If those jets and leptons are from decays of $t\bar{t}$ pairs, the M_{T2} variable should have a maximum value at the top quark mass. Therefore, we impose $M_{T2}((j_1 l_1)(j_2 l_2)) > 180 \text{ GeV}$.

To reduce the combinatorial background, we define another M_{T2} valuable, $M_{T2}((j_1 j_2)(l_1 l_2))$, which has the endpoint at the neutralino mass if both jets are originated from the decay of the Higgs boson. We only use events which have the $M_{T2}((j_1 j_2)(l_1 l_2)) < 200 \text{ GeV}$.

In Fig. 6, we show the invariant mass distribution of j_1 and j_2 . The hatched histogram is the background from the $t\bar{t}$ events. As one can see, the background is reduced efficiently by the M_{T2} cuts. In addition to the peak from the Z boson, we can see a peak of the Higgs boson. By fitting the peak region by a Gaussian function, the Higgs mass is measured to be $m_h = 114 \pm 16 \text{ GeV}$. The error from the choice of the fitting function and the region to fit is not included here.

The use of the jet substructure has been proposed in Ref. [46] to look for boosted Higgs bosons from the neutralino decays. Although the Higgs bosons in this present study are not very boosted, the method may be useful to make the peak sharper.

4 Neutralino vs. Gravitino

Here we comment on the question of how we confirm that the invisible particle is indeed the nearly massless gravitino rather than another neutralino such as the Bino. This question will be important after the discovery of the light stop through the $bZ + \cancel{p}_T$ channel. The clearest signal for the gravitino hypothesis will be the displaced vertex of the Higgsino decay. In the following we consider a case when SUSY scale is too low to observe the displaced Z bosons.

In the case of the prompt decay, in principle, the mass of the missing particle can be measured by combining another independent quantity with the present M_{T2} analyses. For example, the endpoint of the m_{jZ} invariant mass distribution in the stop decay (see Fig. 2) can be such a quantity. The endpoint value is expressed in terms of masses:

$$m_{jZ}^{\max} = m_{\tilde{t}_1} \sqrt{\left(1 - \frac{m_{\chi_1^0}^2}{m_{\tilde{t}_1}^2}\right) \left(1 - \frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right)}. \quad (11)$$

In the $m_{\tilde{G}} \rightarrow 0$ GeV limit, $m_{jZ}^{\max} = (m_{\tilde{t}_1}^2 - m_{\chi_1^0}^2)^{1/2}$. This combination is, however, similar to the one we can extract from the M_{T2} analysis, and thus the constraints we obtain will not be enough to claim the almost massless gravitino. Within the study of the stop pair production, it seems that it remains as a problem to distinguish two scenarios which are drastically different; one with high scale supersymmetry breaking and the other with low scale supersymmetry breaking.

A better way is to look for a Drell-Yan process for the Bino-Higgsino pair production. For a light Bino and a Higgsino there will be significant cross section at the LHC and at the ILC. The final state is Z with a missing momentum without hard jets. The lack of such events will be an indication of the gravitino scenario. Another clear distinction is possible when photon channels are available. If the neutralino (mostly Higgsino) has a small Bino component, we expect $2b + Z + \gamma + \cancel{p}_T$ and $2b + 2\gamma + \cancel{p}_T$. Since the Higgsino/Bino system can give the photon signatures only through a loop diagram, a large number of the photon signal will be a clear indication of low scale supersymmetry breaking.

5 Summary

The LHC experiments are running to look for new physics. If we take the naturalness seriously in supersymmetric models, there should be a rather light scalar top quark and a Higgsino. Also the requirement of the low messenger scale from naturalness suggests that there is a

nearly massless gravitino. The rest of the particles are useless for naturalizing the electroweak symmetry breaking, and therefore can be as heavy as a few TeV. In such a case, the LHC signatures are quite different from the conventional studies.

The approach taken in this paper can be generalized to other models. Taming the one-loop corrections to the Higgs potential always needs a new particle T' which is the stop in supersymmetric case. The presence of T' within the LHC reach would be a robust prediction. We assumed in the study that T' decays into $b + Z + \cancel{p}_T$. If that is the signal, it is clear enough to be distinguished from the standard model processes at the early stage of the LHC experiments.

We have limited our discussion to the MSSM, but the requirements of the light stop and the light Higgsinos are quite general in supersymmetric models whereas the Higgs boson can be much heavier than 120 GeV in extended models. In that case, the Higgsino decay into the Higgs boson is further suppressed or forbidden.

We have constructed a simplified model representing a class of models which solve the naturalness problem. The signal of natural supersymmetry is a clean $2b + 2Z + \cancel{p}_T$. This scenario will be discovered/excluded quite soon at the LHC.

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A Definition of M_{T2}

In this section, we define a useful valuable, M_{T2} [42]. We consider a system in which two particles are pair-produced (which we call “ A ”) and each of them decays subsequently into an invisible particle X and visible ones. In the system, $AA \rightarrow \{\text{visible}(p)X(k)\} +$

$\{\text{visible}(p')X(k')\}$, the M_{T2} variable is defined by

$$M_{T2} = \min_{\mathbf{k}_T + \mathbf{k}'_T = \mathbf{p}_T} \left[\max \{ M_T(\mathbf{p}_T, \mathbf{k}_T), M_T(\mathbf{p}'_T, \mathbf{k}'_T) \} \right], \quad (12)$$

where \mathbf{p}_T is the missing momentum and $p(p')$ is a sum of momenta of visible particles, $p = \sum_i p_i$ ($p' = \sum_i p'_i$). The transverse mass, M_T , is defined by

$$M_T^2(\mathbf{p}_T, \mathbf{k}_T) = m_{\text{visible}}^2 + m_X^2 + 2 \left(E_T^{\text{visible}} E_T^X - \mathbf{p}_T \cdot \mathbf{k}_T \right). \quad (13)$$

If we postulate the true value of m_X in the above formula, we can obtain a parent particle mass m_A as the endpoint of M_{T2} .

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